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Subpicosecond Single-Shot Waveform Measurement using Temporal Imaging

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Abstract

Experimental results from a new single-transient optical recorder with < 300 fs resolution are presented. The system uses a $103\times$ temporal imaging system to expand the waveform which is then recorded with a streak camera.

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Subpicosecond Single-Shot Waveform Measurement using Temporal Imaging

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The recording of single-transient phenomena with a very large time-bandwidth product is a particularly challenging task. While many techniques have been developed to record ultrafast optical signals with sub 100 fs detail [1] they often have practical limitations on the total amount of time that can be recorded or rely on sampling of a repetitive waveform. A waveform manipulation technique known as temporal imaging [2–4] is being developed to overcome some of these limitations. Temporal imaging can expand an arbitrary optical waveform in time while maintaining the shape of the unknown envelope profile, thus allowing it to be recorded by a slower technology with a resolution improved by the magnification of the imaging system. We present here the first single-shot temporal images produced with an upconversion temporal imaging system [5, 6] and recorded with a streak camera.

The experiment performed has three basic parts; generation of a test pattern, 103× magnification of the test pattern with an upconversion temporal imaging system, and recording of the temporal image with a streak camera. A test pattern was actually generated and temporally magnified every period of the laser. We demonstrate single-shot operation by running the streak camera in a single-sweep mode.

The system was tested with a two pulse input pattern generated by propagating an 87 fs pulse from a modelocked Ti:Sapphire laser through a Michelson interferometer. The delay, $\Delta\tau_{\rm in}$, between the two pulses was adjusted in $667.1 \pm .7$ fs steps by varying the length of one arm of the interferometer.

A temporal imaging system (Fig. 1) is produced by cascading input dispersive propagation, a quadratic phase modulation in time which acts as a "time lens," and output dispersive propagation. This is directly analogous to the cascading of paraxial diffraction, quadratic phase modulation in space produced by a normal lens, and further paraxial diffraction used to generate a spatial imaging system. Since imparting a linear frequency chirp is equivalent to imparting a quadratic temporal phase, we are able to implement the time lens by noncollinear sum-frequency generation of the dispersed input signal with a linearly frequency swept ($d\omega/d\tau$) pump pulse. The strength of the time lens is characterized by a focal group delay dispersion (GDD) $\phi''_f = -(d\omega/d\tau)^{-1}$; the amount of GDD required to remove the chirp imparted by the time lens. When these processes are balanced in accordance with the imaging condition $1/\phi''_1 + 1/\phi''_2 = 1/\phi''_f$, a temporal image with magnification $M = -\phi''_2/\phi''_1$ is created. The temporal imaging system is shown in Fig. 1 and presented in more detail in references [5, 6], where repetitive photodiode and sampling oscilloscope measurements demonstrated < 200 fs resolution and a 5.65 ps field of view. A difficulty for single-shot measurements was the low pulse energies. The laser produces 12.5 nJ/pulse, which was split to form the pump and input pulses. After propagating through their respective dispersive delay lines (50% transmission) there was 3 nJ in the pump and 375 pJ/pulse in the signal before mixing in the crystal. The upconversion efficiency and output

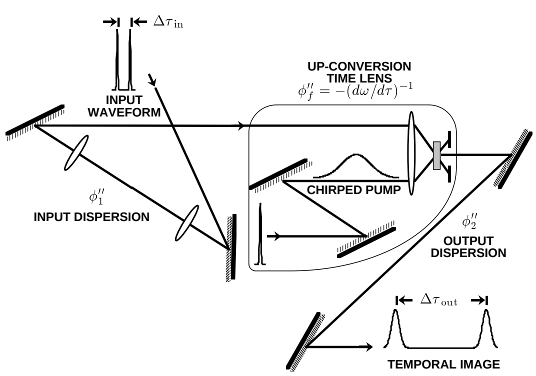

Fig. 1. Upconversion temporal imaging system with magnification $M = +103$.

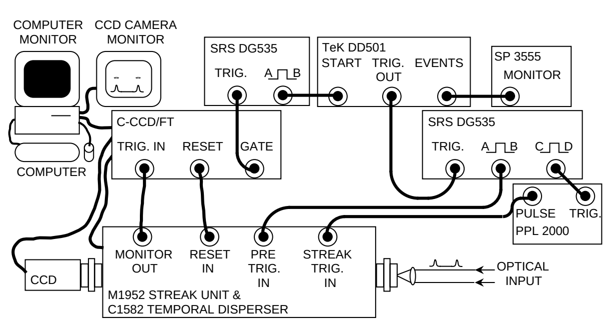

Fig. 2. Streak camera triggering configuration.

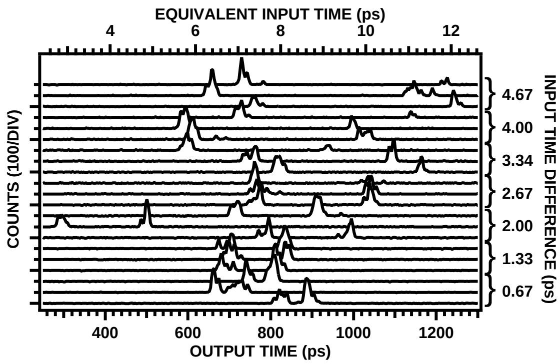

Fig. 3. Three single-shot temporal images recorded for each delay setting, including the trigger jitter.

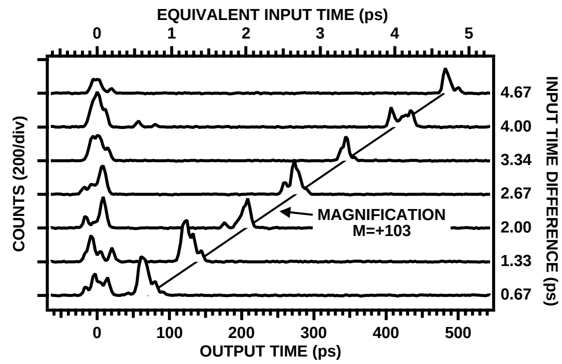

Fig. 4. One image from each input delay setting with the offsets adjusted to remove the trigger jitter.

dispersion losses produced an image with only 0.4 pJ/pulse.

The temporal imaging process actually produces a complete image for every occurrence of the pump pulse. We demonstrated this by recording temporal images with a Hamamatsu streak camera (M1952 Streak Unit & C1582 Temporal Disperser), configured as shown in Fig. 2. A request to record a trace opens the shutter on the CCD camera, resets the streak unit, and produces a trigger pulse from the C-CCD/FT camera controller. The first SRS DG535 delay/pulse generator gives a 10 ms delay to ensure mechanical shutters are open. A trigger synchronized with the laser system is produced in the Tek DD501 digital delay generator by performing a fast AND operation with a photodiode signal internal to the Spectra Physics system (SP 3555 monitor output). A second SRS DG535 is used to generate the two triggers required by the streak camera. First the “Pre Trig In” turns on the microchannel plate (MCP) which was operated near its maximum gain of 10^4, then about 1 μs later a pulse from the Picosecond Pulse Labs 2000 pulse generator triggers a single sweep of the streak tube. When the streak has completed, the MCP turns off to minimize background noise (1.5 counts rms) and the “monitor out” signal triggers the C-CCD/FT to read the CCD. The streak camera was operated on the “2 ns/15 mm” sweep setting, which at an input slit width of 30 μm had a measured impulse response of 10–14.5 ps FWHM, depending on the pulse energy. The slit was subsequently opened to 60 μm to increase the signal but the impulse response was not remeasured.

Figure 3 shows the results of recording three temporal images for each setting of delay between pulses at the input. The jitter in these data is 111 ps rms, primarily resulting from the Tek DD501. In Fig. 4 only one trace per group of three is plotted and the initial times are adjusted to remove the trigger jitter. Also plotted is a line representing the expected $+103\times$ temporal magnification. Clearly, input test pattern changes of 667 fs produced output time delay changes ($\approx$68.7 ps) consistent with predictions. Although noisy, the average duration of the pulses in Fig. 4 is 19.3 ps, which agrees well with the expected pulse widths when the ideal 9 ps impulse response of the imaging system and an assumed 15 ps impulse response of the streak camera are considered. The poor signal-to-noise (S/N) in this experiment is due in part to the low pulse energy and in part to the electronics.

Although further improvements of the S/N and trigger jitter are needed, this experiment demonstrates < 300 fs resolution in a temporal imaging-based single-shot recording system. It is expected that further development of this technology will lead to a new class of single-transient recorders with ultrafast resolution and long record length.

Acknowledgments

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